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Keywords

color glass condensate, gluon saturation, J/Ψ

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Breakdown of k_T -factorization and J/ψ production in dA collisions

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Abstract

In spite of the sweeping coherence effects in high energy hadron and nuclei collisions, k_T -factorization can be recovered for the inclusive gluon production in pA collisions at the leading logarithmic order. In open charm production at RHIC k_T -factorization holds numerically with about 10–20% accuracy. This allows to extrapolate the cold nuclear matter effect observed in light and charm meson production in dA collisions to that in AA ones. Unlike the open charm, the breakdown of factorization in J/ψ production is severe. Indeed, already at the lowest order in gluon density the main contribution to the inclusive cross section is proportional to the square of gluon density in the nucleus. As a consequence, one cannot infer the cold nuclear matter effect on J/ψ production in AA collisions from that in dA . We present the calculation of J/ψ multiplicity in the framework of the CGC (color glass condensate)/saturation and show that it agrees with the experimental data.

1. Introduction

One of the cornerstones of the hard perturbative QCD (hpQCD) is factorization theorems, which state that soft non-perturbative part of the scattering cross section for any hard process can be encoded in universal parton distribution functions (pdf's). ‘Hard’ means that the momentum transfer Q is much larger than any intrinsic hadron momentum scale. According to Gribov, Levin and Ryskin [1], at high energies there is a universal scale characterizing hadronic wave functions – the saturation momentum Q_s – that rapidly increases as a power of energy. One therefore expects that at higher energies factorization is broken down in a wide region of momenta $p_T \lesssim Q_s$. Understanding the structure of inclusive processes in the region where the hpQCD factorization is not applicable is important for quantifying the role of the cold nuclear matter effects in pA and AA collisions. In this article I review our present understanding of the subject and its implications for inclusive J/ψ production.

2. Factorization in inclusive gluon and quark production

Factorization in inclusive gluon production in pA collisions in the low x region was investigated in [2], where the cross section was derived that re-sums all leading logarithmic contributions $\alpha_s \ln(1/x) \sim 1$ (LLA) for a heavy nucleus in the quasi-classical limit $\alpha_s^2 A^{1/3} \sim 1$. One does not expect any hpQCD factorization to apply in this case because higher twist interactions

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of valence quarks and gluons give contributions of order unity. Nevertheless, despite the fact that individual diagrams break factorization in covariant and light-cone gauges, the final re-summed expression can be cast in the k_T -factorized form. Unlike in hpQCD, the physical quantity that is factorized – the unintegrated gluon distribution $\varphi(x, Q^2)$ – is not soft and can be calculated perturbatively owing to existence of a hard scale $Q_s \gg \Lambda_{\text{QCD}}$. Another surprising fact is that contrary to naive expectations $\varphi(x, Q^2)$ is related not to the momentum space Fourier-image of the nucleus gluon field correlation function $\langle \underline{A}(0) \cdot \underline{A}(\underline{x}) \rangle$, but rather to the Fourier-image of $\nabla_r^2 N(\underline{r}, \underline{b}, y)$, where $N(\underline{r}, \underline{b}, y)$ is the imaginary part of the forward elastic scattering amplitude of a color dipole of size \underline{r} at impact parameter \underline{b} and rapidity $y = \ln(1/x)$ in the heavy nucleus. We will see that although the inclusive gluon production in pA collisions is the only known case where k_T -factorization survives, factorization of the multipoles in the transverse coordinate space is the general feature of the low- x cross sections. It must be stressed that this multipole factorization does not imply hpQCD factorizations (k_T or collinear ones) and neither opposite is generally true. A k_T -factorization formula derived in [2] led to successful phenomenology of inclusive hadron production in dA collisions at RHIC where the suppression of hadrons at forward rapidities and the Cronin enhancement at mid-rapidity were qualitatively predicted [3, 4] and then quantitatively described in the CGC framework [5].¹

k_T -factorization in pA collisions does not imply any factorization in AA . In fact, no rigorous analytic result for an inclusive process exists in the latter case. As in pA , individual diagrams in any gauge break the hpQCD factorization. It is however possible that the re-summed result exhibit a simpler structure than the individual diagrams. Thus, using a theoretically motivated conjecture it has been shown in [7] that inclusive gluon production in AA can be written in a form that breaks k_T -factorization only logarithmically. Based on this conjectured approximate k_T -factorization, one can derive an important qualitative conclusion about the observed strong suppression of inclusive hadron production in AA collisions at RHIC. Since the analogous process in pA collisions in the same kinematic region exhibits Cronin enhancement, we conclude that the suppression in AA is not a cold nuclear matter effect. We see that factorization plays a key role in establishing existence of a new form of nuclear matter produced in AA collisions.

Production of heavy quark in pA collisions at low- x was calculated in [8, 9, 10, 11]. One expects that the hpQCD factorization is applicable if the saturation momentum is much smaller than the quark mass m [12]. At RHIC $Q_s \sim m$ for charm and bottom, hence factorization is broken in both cases. Indeed, analysis of [13] indicates that the semi-classical calculations of [8, 10] disagree with k_T -factorization by 10-20% at the t -channel gluon transverse momenta around m . A common feature of the inclusive gluon and heavy quark production is that at transverse momenta much higher than the saturation momentum, cross sections reduce to the LO hard perturbative ones and consequently factorize. In other words, the hpQCD factorization is restored in the kinematic region where the operator product expansion is applicable. It is important therefore that the leading term in the twist expansion coincides with that of hpQCD. This is not so in the case of the J/ψ production.

¹An alternative approach that incorporates the coherence effects, but attributes the observed suppression to the peculiarities of the fragmentation process is presented in [6]. The two mechanisms can be discriminated by observing whether the suppression pattern scales with x_{Au} (CGC) or x_D (fragmentation).

3. Factorization breakdown for inclusive J/ψ production in nuclear collisions

The mechanism of J/ψ production in high energy nuclear collisions is different from that in hadron-hadron collisions [14, 15, 16]. Consider first the J/ψ production in pp collisions. At high energies formation time of the J/ψ wave function is much larger than the size of the interaction region. Indeed, in the nucleus rest frame, the former is $2M_\psi l_c/(M_{\psi'} - M_\psi)$ where $l_c = 1/(xM_N) > R_A$ is the coherence length and $M_{\psi'} - M_\psi \ll M_\psi$, while the latter is R_A . Therefore, we need to take into account only interaction of the $c\bar{c}$ pair with the nucleus. This interaction however depends on the quantum state of the $c\bar{c}$ pair. In the color singlet model it is in the 1^{--} color singlet state while in the color evaporation model it can be in any state with invariant mass below the D -meson threshold. Although the color singlet model is physically well-motivated, it underestimates the J/ψ yield. We therefore assume that $c\bar{c}$ is produced in the 1^{--} state with any color. Since none of the existing approaches to J/ψ production (including the non-relativistic QCD model) in pp collisions agrees with all the available data, one may doubt the applicability of our model for J/ψ production in pA collisions. Note, however, that there are indications that solution to the J/ψ production puzzle lies in understanding the role of the higher twist contributions [17]. In heavy nuclei, where $\alpha_s^2 A^{1/3} \sim 1$, only certain higher twists are enhanced – namely those corresponding to interaction of the color dipoles with different nucleons. Therefore, higher twist contributions in pA collisions can be taken into account in a systematic way.

Consider now two possible production mechanisms at the lowest order in α_s illustrated in Fig. 1: (A) $g + g \rightarrow J/\psi + g$, which is of the order $O(\alpha_s^2 A^{1/3})$ and (B) $g + g + g \rightarrow J/\psi$, which is of the order $O(\alpha_s^3 A^{2/3})$. Since $\alpha_s^2 A^{1/3} \sim 1$, the mechanism in Fig. 1-B is parametrically enhanced. Notice, that this leading contribution explicitly breaks k_T -factorization as it is proportional to $xG(x_1)[xG(x_2)]^2$.

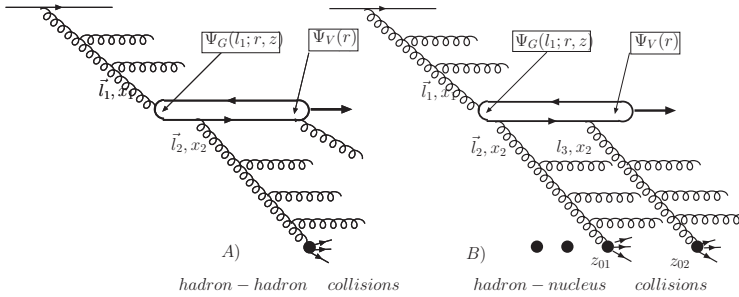


Figure 1: The process of inclusive J/ψ production in (A) hadron-hadron and (B) hadron-nucleus collisions.

At high energies, when $l_c \gg R_A$, all possible scatterings of the $c\bar{c}$ pair inside the nuclear medium must be taken into account. The number of scatterings on each diagram is restricted however by the requirement that the $c\bar{c}$ pair is in 1^{--} state. In other words, the number of inelastic interactions of the charm dipole in the nucleus must be even. The corresponding scattering amplitude reads

$$T_{\text{in}}(\underline{r}, \underline{r}') = e^{-r^2 Q_s^2/8} e^{-r'^2 Q_s^2/8} \left(\cosh[2\underline{r} \cdot \underline{r}' Q_s^2/8] - 1 \right), \quad (1)$$

where r and r' are the $c\bar{c}$ dipoles in the amplitude and in the complex conjugated one. Of course, there is no such restriction on the elastic amplitude involving exchange of gluon pair with the

vacuum quantum numbers. The elastic amplitude is given by

$$T_{\text{el}}(\mathbf{r}, \mathbf{r}') = \left(1 - e^{-r^2 Q_s^2/8}\right) \left(1 - e^{-r'^2 Q_s^2/8}\right). \quad (2)$$

To obtain the cross section one has to convolute these amplitudes with the virtual gluon and J/ψ wave functions, given in e.g. [18, 19].

Experimental data is expressed in terms of the nuclear modification factor defined as

$$R_{AB} = \frac{\int_S d^2b \frac{d\sigma_{AB \rightarrow J\psi}^J}{dy d^2b}}{A B \frac{d\sigma_{pp \rightarrow J\psi}}{dy}}, \quad (3)$$

where S stands for the overlap area of two colliding nuclei. We calculate the J/ψ production in pp collisions according to Fig. 1A by replacing T_{in} in (1) with

$$T'_{\text{in}}(\mathbf{r}, \mathbf{r}') = e^{-(\mathbf{r}-\mathbf{r}')^2 Q_s^2/8} - e^{-r^2 Q_s^2/8} e^{-r'^2 Q_s^2/8}, \quad (4)$$

where no restriction on the number of inelastic interactions has been made. Note also that the overall normalization is still not determined since the pp cross section is proportional to the probability of soft gluon emission. We approximate this probability by a constant.

To take into account the low- x quantum evolution we recall that the initial condition for the BK [20, 21] evolution equation is given by the Glauber–Mueller formula for the forward dipole–nucleus elastic scattering amplitude [22]

$$N(\mathbf{r}, \mathbf{b}, y_0) = 1 - e^{-\frac{1}{8} \mathbf{r}^2 Q_s^2(y_0)}. \quad (5)$$

Therefore, we can incorporate the evolution effects by writing the scattering amplitudes (1),(2),(4) in terms of the amplitude N and letting the latter depend on rapidity y as dictated by the BK equation. Energy evolution of $N(\mathbf{r}, \mathbf{b}, y)$ is taken into account using the KKT model [5] which parameters are fixed to describe the inclusive hadron production in pA collisions. The result of the calculation is shown in Fig. 2. We observe that a good agreement with experimental data.

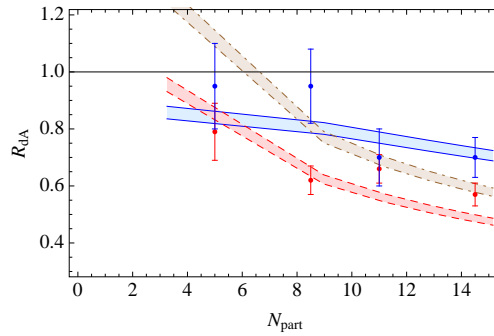


Figure 2: Nuclear modification factor for J/ψ production in heavy-ion collisions for different rapidities. Solid (blue) line corresponds to RHIC $y = 0$, dashed (red) lines – RHIC $y = 1.7$, Dot-dashed (brown) line – LHC mid-rapidity. Experimental data from [23].

We expect that the breakdown of the hpQCD factorization has important impact on the J/ψ production in AA collisions. Because of this the magnitude of the nuclear modification factor R_{AA} cannot be inferred from the dA calculations.

4. Conclusions

We discussed the breakdown of the hard perturbative factorization in the gluon saturation region. This happens due to coherence effects over the entire nuclear length. This effect invalidates approaches that use pdf's parametrized to include the "nuclear shadowing" corrections. The very notion of pdf as a universal quantity is not applicable for processes with typical momentum transfer of the order of the saturation momentum. Fortunately, rigorous analytical perturbative results can be derived for processes involving scattering off heavy nuclei. In particular, a new mechanism of J/ψ production in pA collisions has been suggested. It predicts dependence on nuclear weight A and rapidity y which is in a good agreement with the experimental data. We plan to extend our calculation to heavy-ion collisions and also calculate the J/ψ polarization. Our approach can be applied to pp collisions as a model resummation of higher twists.

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References

- [1] L. V. Gribov, E. M. Levin and M. G. Ryskin, Phys. Rept. **100**, 1 (1983).
- [2] Y. V. Kovchegov and K. Tuchin, Phys. Rev. D **65**, 074026 (2002) [arXiv:hep-ph/0111362].
- [3] D. Kharzeev, Y. V. Kovchegov and K. Tuchin, Phys. Rev. D **68**, 094013 (2003) [arXiv:hep-ph/0307037].
- [4] J. L. Albacete, N. Armesto, A. Kovner, C. A. Salgado and U. A. Wiedemann, Phys. Rev. Lett. **92**, 082001 (2004) [arXiv:hep-ph/0307179].
- [5] D. Kharzeev, Y. V. Kovchegov and K. Tuchin, Phys. Lett. B **599**, 23 (2004) [arXiv:hep-ph/0405045].
- [6] B. Z. Kopeliovich, J. Nemchik, I. K. Potashnikova, M. B. Johnson and I. Schmidt, Phys. Rev. C **72**, 054606 (2005) [arXiv:hep-ph/0501260].
- [7] Y. V. Kovchegov, Nucl. Phys. A **692**, 557 (2001) [arXiv:hep-ph/0011252].
- [8] F. Gelis and R. Venugopalan, Phys. Rev. D **69**, 014019 (2004) [arXiv:hep-ph/0310090].
- [9] K. Tuchin, Phys. Lett. B **593**, 66 (2004) [arXiv:hep-ph/0401022].
- [10] J. P. Blaizot, F. Gelis and R. Venugopalan, Nucl. Phys. A **743**, 57 (2004) [arXiv:hep-ph/0402257].
- [11] Y. V. Kovchegov and K. Tuchin, Phys. Rev. D **74**, 054014 (2006) [arXiv:hep-ph/0603055].
- [12] D. Kharzeev and K. Tuchin, Nucl. Phys. A **735**, 248 (2004) [arXiv:hep-ph/0310358].
- [13] H. Fujii, F. Gelis and R. Venugopalan, Phys. Rev. Lett. **95**, 162002 (2005) [arXiv:hep-ph/0504047].
- [14] D. Kharzeev and K. Tuchin, Nucl. Phys. A **770** (2006) 40.
- [15] D. Kharzeev, E. Levin, M. Nardi and K. Tuchin, arXiv:0809.2933 [hep-ph].
- [16] D. Kharzeev, E. Levin, M. Nardi and K. Tuchin, Phys. Rev. Lett. **102**, 152301 (2009)
- [17] J.W. Qiu, this proceedings.
- [18] Y. V. Kovchegov and L. D. McLerran, Phys. Rev. D **60**, 054025 (1999) [Erratum-ibid. D **62**, 019901 (2000)] [arXiv:hep-ph/9903246].
- [19] E. Gotsman, E. Levin, M. Lublinsky, U. Maor and E. Naftali, arXiv:hep-ph/0302010.
- [20] I. Balitsky, Nucl. Phys. B **463**, 99 (1996) [arXiv:hep-ph/9509348].
- [21] Y. V. Kovchegov, Phys. Rev. D **60**, 034008 (1999) [arXiv:hep-ph/9901281].
- [22] A. H. Mueller, Nucl. Phys. B **335**, 115 (1990).
- [23] S. S. Adler *et al.* [PHENIX Collaboration], Phys. Rev. Lett. **96**, 012304 (2006) [arXiv:nucl-ex/0507032].